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A conceptual approach for military data fusion

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Abstract

Military operations become more and more complex. Information overload, and uncompleted and uncertain data made military information system design a challenge that would confer or withhold information superiority. The latter could represent military superiority especially in complex warfare such as urban operations or counterterrorism. This paper proposes a process for military information system design. This approach is based on a merge between the existing fusion frameworks on the one hand, and on the author's experience in data fusion, on the other hand. Specifically, the design is based on system objectives and accuracy requirements, constrained by a determined sequence of events, in this case detection, identification, tracking and estimate of future states (DITE). Then, a five-dimension structure is proposed for data modeling and management: space (x,y,z), time (t) and possible worlds (w). On this basis, data exploitation and resource management could be performed with regard to network inferences, data perfection conditions and general data fusion approaches. A learning process could enhance the system by an intelligent component that would perform optimization.

1. **Introduction**

In the area of R&D, data fusion has become in the last years a proposed solution to a broad range of problems, from command and control system design to sensor performance optimization. The need for fusion comes mainly from the objectives of information overload reduction, accuracy improvement, and exploitation of partial or uncertain knowledge. A possible definition for data fusion [Li *et al.*, 1993] could be generalized to "the combination of a group of inputs with the objective of producing a single output of greater quality and reliability". This definition has an advantage over other definitions proposed by [Steinberg, 2001], [Klein, 1993] and [Wald, 1999] by being generic, straightforward and unambiguous.

[Solaiman, 2001][Steinberg, 2001][Wald, 2001] defined data fusion taking into account -to different degrees- data, observation, feature, decision and knowledge. This paper uses the representation proposed by [Solaiman, 2001] for its particular clarity and for its unified view of data processing. Figure 1 illustrates Solaiman's representation of data processing.

Having defined data fusion and its applications, the next step is devoted to the design of the data fusion system. [Solaiman, 2001] and [Steinberg, 2001] have already provided good frameworks for data

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fusion. Their frameworks include the main concepts involved in the already existing data fusion research. However, there are little conceptual overlaps between the two works since each of the two researchers look at a distinct aspect of the same problem. [Solaiman, 2001] focuses on the fusion process itself while [Steinberg, 2001] paid more attention to system design, without putting much emphasis on the fusion process.

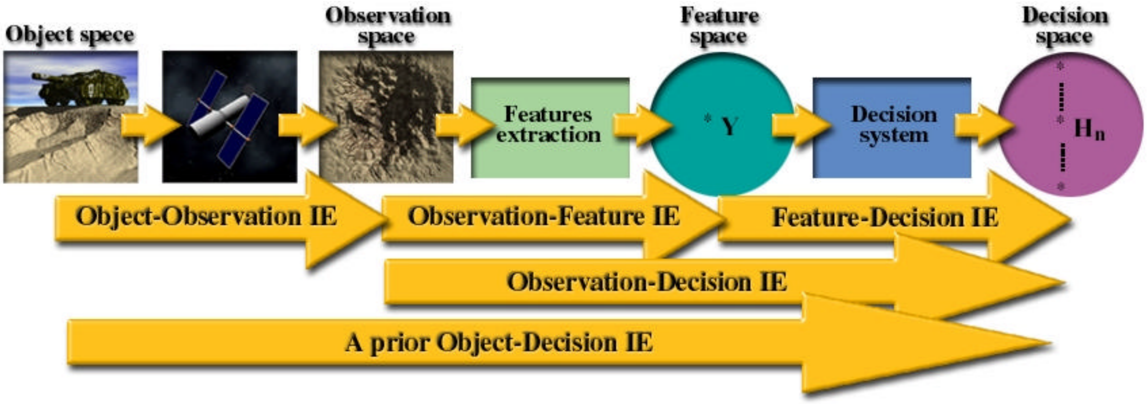

Figure 1: Data processing – from Object, observation, feature and decision spaces [Solaiman, 2001].

The main objective of this paper is to propose steps for general **information system design**, comprising data-fusion capability, within the military area. This task is based on the two references mentioned above but enhanced by the author's comments and integration view. The information system would be considered as including all actors or components. The emphasis will be put first on data exploitation and second, on data source management.

The particularity of military information system design is explained by its need for robustness i.e. accuracy, reliability and credibility. In other words, these systems handle human lives, exploit heterogeneous data sources, and involve limited resources (individuals, material, time, etc). Moreover, the huge amount of data inputs, the unavailability of many cases to understand a problem, and the omnipresent threat of enemy deception operations. All of these particularities make the design of a military information system a challenge that would confer or withhold information superiority, which could represent military superiority especially in complex warfare such as urban operations or counterterrorism.

This paper proposes a conceptual approach for **information system design** based on the three-tiers architecture [Orfali, 1999] with respect to the military requirement for robustness. The system is then considered as an object with three facets: interface, storage and processing. Figure 2 illustrates a basic representation of this architecture. The interface is considered as the link between the physical system and its users. The interface is also the system's facet that communicates with other systems (inter-system communications). The resulting exchanges must respect common ontology, security, and other inter-system or inter-agency requirements. Section 2 presents this facet for the definitions of the system's objective/goal, of the accuracies, and of the sequence of events determination. Section 3 focuses on a possible data storage structure. It is based on the world physical representation of space and time. A possible-worlds dimension could enhance the system to support the *a priori* knowledge of the possible worlds, the simulations, as well as the recording of past events occurred within the system use.

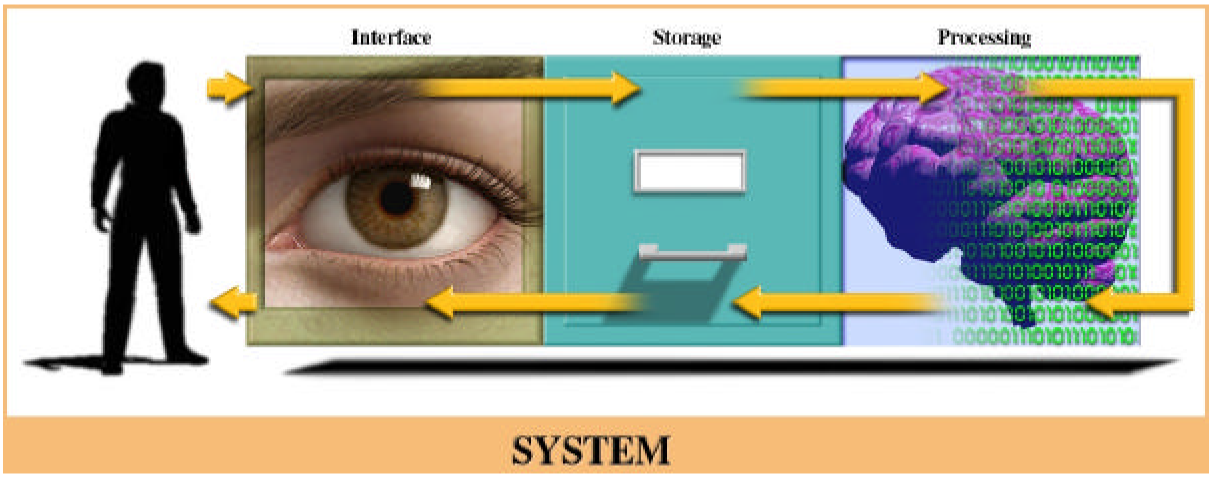

Figure 2: Three-tiers architecture

Section 4 presents the processing unit of the proposed information system design. Data fusion and resources management capabilities are proposed followed by a learning component definition, which introduces "intelligence" within the system. Section 5 concludes this document with a summary of the proposed approach, followed by a discussion about the next steps related to the area of military information system design, implementation and application.

Military information system definition and constraints have to be introduced before the three-tiers facets. A "generic" system definition could be stated as "any organized assembly of resources and procedures united and regulated by interaction or interdependence to accomplish a set of specific functions" [U.S. DOD, 1994]. Figure 3 schematizes a system at its simplest level: inputs being processed to give an output.

Figure 3: System definition by inputs-processing-output

From the previous listing of military system particularities, the next constraints could be suggested: semi-automation at the decision level, human factors control, openness, and the clarity for directions.

Only exceptions should involve automation and decision taking for system components for decision taking. Since responsibility for human life is involved, the decision process, directly related to a prior established goals (section 2.1), should involve a human control. This implies an architecture where humans are dealing with machines. The objective should then be to exploit the strengths of both the human (qualitative) and the machine (quantitative).

As in any organization, the human factor should be assessed. A major point is to keep the physical-system as a tool, which objective is to enhance decision-taking process by the human. Special care should then be given to the dynamic between the system's physical components and human actors.

System openness is a characteristic that could allow a system to evolve over time. Hence, the adding of new components, or the removal of past components, should be performed without architectural changes. Openness may be performed by the use of multi-agent architecture [Pigeon *et al.*, 2000b], which is fully compatible with three-tiers approach. For instance, each system's actor, including both human and physical components, could be considered as an agent, which can be itself considered as a system by itself, a subsystem of the main information system. As is the case within military training, these agents possess general as well as specialized capabilities. An objective then is to develop agents that respect equilibrium between specialization and modularity. This objective might be reached by the use of a learning component that optimizes specialization.

Finally, the direction phase, the first of the intelligence cycle phases [Canada National Defence, 1998], could be achieved by clear identification of the system's objectives/goals (definition, expected time and/or conditions for completion, required accuracy), the capacity to achieve them (based on all system components/actors capabilities in accordance with the application context) and the course of action (COA) to achieve them. The next section presents the details related to the clarity of direction.

2. **Interface**

This section presents the link between the physical system and its users in order to define the objectives/goals of the components, their accuracies, and the system's sequence of events.

2.1 ***Objectives/Goals***

The objectives –goals- could be identified on the basis of the actor/components roles and responsibilities. From a military perspective, goals are defined with regard to the following three levels of abstraction: the strategic level, the operational level, and the tactic level. The membership to a singular level could be seen as dependent on the organizational responsibility, for instance political/civil or military: from corps, division, and brigade, to platoon. This representation is made for direction clarity. However, it could not be suitable for every case. For instance, within the urban operations context, the border between the strategic and tactical levels is somewhat difficult. For instance, the presence of a high density of civilian can imply politics within platoon commander actions, then moving these actions from the (traditional) tactical level to the strategic level.

From this representation, objectives (and/or centers of gravity) are identified with respect to the next constraints. Data and resources involved with its collection have both to exist and to be available (being complete or partial, direct or indirect). Context and problem variability (including the system state) have to be known.

2.2 *Required accuracy*

Numeric or symbolic accuracy has to be paired with each single system objective. At this step, the complexity/level of details is set. The required complexity determines the representation.

For example, the conceptual representation of a spatial data structure (section 3.1) falls into the complexity requirements. This could be stated as signal (level 0), object (level 1) and situation (level 2) [Steinberg, 2001]. These three levels could also be described from an oriented-object perspective [Booch *et al.*, 1999]. Within this formalism, the object is characterized by attributes and functions. Interactions between objects are defined as inherence, aggregation, communications, and other relationships (e.g. dependence and ownership). The Steinberg's levels 0 to 2 became then a representation of a same knowledge about data., as the object definition could involve a situation representation.

For example, a same instance could be represented both as an object or as a situation (its attributes being represented as signals). A light armored vehicle (LAV) instance could be represented by a single object (the LAV itself), or by an aggregation of objects (e.g. the frame, the wheels, and the weapons). The aggregation case is considered being a situation (Steinberg level 2), since it involves relationships between the objects. The choice of representation is related to the required accuracy.

This example can also be applied to the system definition. Figure 1 illustrates a simple form of system, which is schematized again in Figure 4a. Figure 4b represents a zoom on the figure 4a system. For instance, three components are schematized. Each of these components could be represented by a single system as shown in figure 4c, and so on. Figures 4a to 4c are different representations, from different complexity levels, of a same system.

The system of system appellation could then be used when dealing with the integration/merging of the existing/legacy systems, multiple ownership systems, multiple languages system, etc. [Solaiman, 2001], when talking about fusion capabilities, notes that "…approaches are motivated and mainly influenced by the type of applications".

Data requirements could be identified from accuracy. They could be adaptively based on the context i.e. possible-worlds attributes (section 3.3). For instance, in urban operations, the intelligence requirements checklist [U.S. Army, 2000] includes the city infrastructure. In accordance with this requirement, the representation could be two-dimension (2D) maps or three-dimension (3D) maps, which might or might not represent the inside of buildings or sub terrains, the facilities such as energy and communication networks, etc. Definition of objectives and related accuracy could correspond to the priority intelligence requirement (PIR). Then, intelligence preparation of the battlefield (IPB) could be achieved.

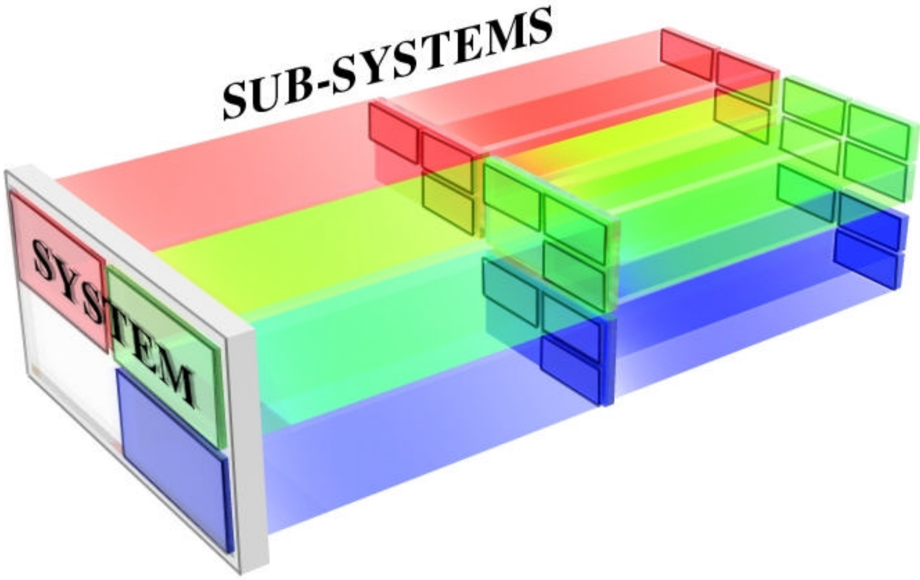

Figure 4: Arbitrary levels of object representations: system, and system of systems

2.3 *Sequence/steps to achieve objective-accuracy*

The next steps are a generic sequence proposal for objectives achievement. These steps are sequential: they detect, identify, track and estimate future state (DITE). They are fulfilled with regard to the context of the problem to solve.

- **Detect**: discover or perceive the existence of an object.
- **Identify**: quantify object attributes in order to meet conditions for perfect exhaustiveness and/or precision (section 4.4.1).
- **Track**: monitor the object with regard to the time dimension (section 3.2).
- **Estimate future state**: predict an object (including situation) status over time, or more particularly a damage estimate for a possible engagement, as stated by [Steinberg, 2001] level 3.

This sequence is a discrete representation of a continuum. For instance, the *identify* step can be defined as a composite of the two sub-steps that aim identification of the

1. object **category**: exclusivity (section 4.4.1) condition is not met i.e. exclusivity is considered being imperfect with regard to the context of the problem.
2. object **instance**: exclusivity condition is met i.e. exclusivity is considered being perfect with regard to the context of the problem.

The sequence of events could use other representations. For instance, [Hurley, 2001] proposes a sequence for urban operations achievement: understand, shape, engage, consolidate and transition (USECT). Another representation of the same problem can be stated by Command, Sense, Sustain, Shield, Act (CSSSA). As within DITE the estimation of future state (E) involves the previous sequence (DIT), within USECT, the SECT phases involves the U phase. For the CSSSA, the act phase (A) is involved within each of the CSSS. Within the three-tiers facets, processing capabilities and/or data storage, could be used at the interface level. Therefore, it becomes a question of problem definition or representation (attention focusing).

From this step, a collection plan could be generated and performed, based on the characteristics of system storage (section 3) and of processing (section 4).

3. **Storage**

The structure of data-storage has to be both generic -to allow system evolution- and formal -to facilitate data processing-. The proposed structure is based on the world physical representation of space and time.

3.1 ***Space***

Using the space representation (x,y,z coordinates) as data-storage structure for an object offers the advantage of being both generic and formal. Whether a single infantryman or an order of battle (ORBAT) can be modeled within these space coordinates. For both, space coordinates could characterize the instances of class. Moreover, the relationships between the ORBAT objects (situation level) and the spatial coordinates of each component can be obtained from abstraction zoom on the desired object. Non-spatial information can be stored within the object's attributes section (example: cultural knowledge related to individuals, people networks, situations). Spatial and non-spatial accuracy should characterize object attributes. Finally, the object physical constraints can be stored within the object operations section.

For example, a fuzzy value such as the enemy "will to fight" could be stored within an enemy ORBAT instance attributes section. It could even be stored on sub-parts of the ORBAT if it applied only to a subset of units. In the same way, terrain navigation constraints for a particular tank model could be stored within the object class allowed operations section, and so on.

3.2 ***Time***

The dimension of time has to be formalized in order to handle the evolution of spatial objects (including situations) over time. Also, the time dimension might be used to store knowledge related to a resource capability available over time. Proposal is to consider the time being handled as an object attribute. From this dimension, primitive estimate of future state could be assessed. However, prediction involves the exploration of all system parameters and possibilities for single or multiple contexts. Another dimension is proposed to handle these "possible worlds".

3.3 *Possible-worlds*

The possible-worlds concept is the result of a dimension (w) added to the previous space (x,y,z) and time (t) dimensions. Hence, situation possible COA could be stored within a (x,y,z,t,w) format. Moreover, the predictions (estimation of future states) and the a prior knowledge related to COA could be generated within this format. Historic of system component parameters from experiences, used cases, could be managed within this dimension, which is the main data source for system learning and process refinements. All of the stored data constitutes the system's intellectual patrimony.

4. **Processing**

The processing unit is the brain of the system. It performs data exploitation to meet the goals and their associated accuracies. In military information system design, the data-fusion and the resource management capabilities are the essential for superiority. As final enhancement, a learning component might record every system attribute and/or operations, and use them for simulation and optimization.

4.1 *Data exploitation & resource management*

Duality between hypotheses (goal, accuracy) and resources (human or physical sensors, databases) seems natural, since they rely on each other. As stated in the introduction, the main body of the processing facet focuses on data exploitation perspective. However, section 4.1 ends with a brief discussion about the resource management.

4.1.1 *Data exploitation*

The data exploitation is performed from sensor outputs & a prior knowledge, which could involve past experiences, decisions, rule sets, problem conceptualization, etc. From this knowledge, the DITE sequence could be achieved. Considering the time attribute as being accomplished or unaccomplished, with reference of system current time, the letters making up *DITE* stand for the following process:

> **Detect**: Change perception from set of time-accomplished data.
> **Identify**: Information gathering for object attributes quantification, which can include the latter change detections over time-accomplished data.
> **Track**: Change detections from an identified object instance over time-accomplished data.
> **Estimate future state**: Generation of time-unaccomplished data/possible world(s), then associated to possible COAs.

From *a priori* knowledge, inference networks can be generated. These networks are nothing but conceptual maps showing possible paths to take in order to navigate from one point to another. These logical paths relate data to objectives with checkpoints that can merge data and decisions. They are firstly defined from a prior knowledge of problem solving. Subsequently, they can be enhanced by a learning component.

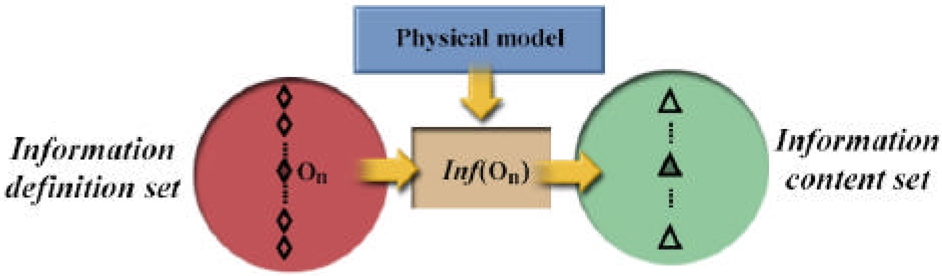

Figure 5: Data (Information) definition set – physical model – data (information) content set [Solaiman, 2001]

A plain form of inference network is schematized by the relationship in figure 5 [Solaiman, 2001]. The data definition set is linked to data content set. The relation between the two sets (e.g. physical model and psychological model) corresponds to an inference. When more than two sets are linked together, a network is generated. When more than one link connect two sets, data fusion has to be performed. Fusion is required to reduce links redundancy (information overload) and/or to improve accuracy by the summation of partial data or uncertain data.

Data fusion can solve the problems related to the complexity of the threats, the ambiguity of partial warnings, and the ability of plotters to overcome obstacles, to manipulate information and to deceive victims. Past failures attributed to an overload of incomplete warnings could then have been avoided by the use of data fusion.

Example: A PIR can state "where the enemy unit x will cross the river?" Image intelligence (IMINT) and human intelligence (HUMINT) sources, and their analysts could perform the next tasks:

IMINT: From mixed optical and radar imagery, the steps detect and identify (DI) can be applied for bridges included within area Xi, Yi, Xj, Yj. From the same sources, the same process is performed for roads. From knowledge related to unit x (e.g. vehicle categories and possible objectives), roads (e.g. width and slopes), and bridges (e.g. width and weight capacity), an analysis is achieved to select the most promising path(s) for unit x.

HUMINT: For the same problem, a HUMINT source might collect information related to unit x (or its higher chain of command) intentions and state (e.g. vehicle states, anticipated movements, and will to fight). From the analysis, answers might be proposed for the unit x most promising location(s) to cross the river.

Hence, for this PIR, IMINT and HUMINT sources might get solutions that require a fusion process i.e. each source propose a (possible different) set of weights for the solution hypotheses. However, at IMINT and HUMINT sub-analysis levels, their data is complementary without overlap. The requirement for fusion is then not always present within problem solving process. It depends on the data overlap with respect to the capacities of the sources exploiting it.

It might seem obvious that a system output could be enriched from multiple heterogeneous inputs that present redundancy and partial views of the same problem. However, in order to ensure the coherence for inference and for the data fusion process, a common reference has to be found for the definition of links. [Steinberg, 2001] refers to a similar process named data alignment. A condition for this process completion is the knowledge related to data imperfection elements.

[Solaiman, 2001] defined a data (information) perfect element as respecting the four conditions: exhaustive, exclusive, precise and certain.

The exhaustive condition means that a set of objective hypotheses, object candidates, is complete with regard to the problem. It concerns the inference network ability to connect each piece of data (e.g. object, attributes, operations, and relationships) to all possible solutions, COA, etc. When exhaustiveness is met, there is occurrence of the “closed world” assumption. As an example, the exhaustiveness condition could mean that for a particular instance of weapon, the inference network is able to connect to ALL existing owners, without exceptions.

The exclusive condition means that the object *i* is unique and that the occurrence of all its parameters concerns only that object. In the area of databases, the key field requirement concerns the exclusive condition. For instance, an individual name is not enough to characterize somebody as unique i.e. without confusion. With regard to the context, the national identity number could be enough to meet exclusiveness. In some other context, digital prints could be added, etc.

The precise condition means that for single data, a single object relationship exists. Hence, a national identity number is precise within a country, since it links to a unique person. For person identification, a military rank is not precise, even if it does restrict a search. Exception occurs if the rank is unique within an army. For instance, data about a five stars general could lead to a unique person, then this data (five stars general) is precise. The concept for precision is analogous to the concept for exclusiveness. The difference between them is that the exclusiveness concerns objects, as precision concerns links.

The certainty condition is the ability to identify an object without doubt. It is dependent on source reliability and information credibility [Canada National Defence, 1998], and generally on all of the system’s data, especially decisions.

The thresholds of the four conditions for perfect data element are defined with regards to the problem representation. For instance, exhaustiveness is so complex to cover, exception made for real simple cases that could almost not be met in “reality”. For example, probabilities state, as axiom, that distribution generation must be based on a number of observations that tends toward infinity. It does explain why probabilities are often unsuited for complex problems. However, based on the system’s *a priori* knowledge and on the problem context, a limited number of inferences or COAs could be sufficient, and then closed-world assumption can be made. Exclusiveness can exist in reality but be unavailable from the sensor observation space. For instance, since a satellite image resolution is limited, mixed content pixel could occur. Consequently, data is non-exclusive in the observation space. Precision being a type of accuracy (section 2.2), the same examples could be used to demonstrate its dependence to the context of the problem. Finally, certainty is depends on the function of fitness used for learning (including human evaluations). From the perfection element conditions, it became possible to categorize the main data fusion mathematical approaches. Table 1 presents a succinct summary of these links; exhaustiveness and certainty conditions being considered met *a priori*.

Exclusiveness	**Impreciseness/ inaccuracy**	**Mathematical approaches for data fusion**
x		Probabilistic (Ex: Bayesian networks)
x	x	Evidential (Ex: Dempster-Shafer)
		Ambiguous (Ex: Fuzzy logic)
	x	Possibilistic (Ex: Possibilities)

Table 1: Data imperfection and mathematical approaches for data fusion

For instance, an inference network involving fusion could be related to an operational objective that requires the annihilation of the enemy "will to fight". This data content, the enemy will to fight, should be considered as a fuzzy value ranging from 0 to 1. The *a priori* knowledge about the enemy can specify that its will to fight relies on the number of its supporters (probabilistic uncertainty) and its resources (fuzzy membership to *low* and *high* functions). The latter element could depend on armament (e.g. number of armored vehicles and infantry), energy (e.g. petroleum and gas), health (e.g. hospital and food), media (e.g. radio, TV, and newspaper), etc. A special care must be given to the characterization of single data elements at each level. Hence, data alignment will be smooth and the system strengths for quantification will be exploited.

The approaches presented in table 1 suggest that fusion can be achieved at different levels: data, decisions and models. From the previous discussion, data and decisions can be grouped together. Model fusion describes the process of combining inference links together in order to produce a single inference link of improved quality. For example, these links could be mathematical models [Pigeon *et al.*, 2001a] that, taken separately, do not allow inference from a data source to a solution, but taken together can bring the system to a single solution. Model fusion can also be applied to mixed data fusion, i.e. pieces of data characterized by different imperfections. This area is not well explored. Few works have approached the problem. For example [Pigeon *et al.*, 2000a][Pigeon, 2001c] proposed an approach for mixed probabilistic and evidential fusion, and [Leduc *et al.*, 2001] proposed an approach for ambiguous and evidential fusion. As stated previously, fusion involves combinations of links for the ranking of hypotheses of solution. The decision process is then a separate step that completes the fusion process by the selection of a solution from the hypotheses set.

4.1.2 *Resource management*

[Steinberg, 2001] and [Ng and Ng, 2000] insist on the duality between the fusion process and the resources management. Particularly, from the author of this article point of view, it might be a question of duality between decisions and resources management. From a resource management facet, the previous steps proposed as DITE and dedicated to IPB or more precisely to intelligence direction, collection, processing and dissemination can be applied to general resources management or more particularly to the logistic preparation of the battlefield (LPB). Hopefully, the knowledge related to the resources is being under the system's ownership (*a priori* knowledge about BLUE compared to RED). Thus, the DITE sequence should be simplified to the remaining TE steps, track (T) and future states estimation (E). As a consequence, at the information system level, the system should be capable to update the intelligence collection plan based on its resources TE related data. Similarly, at the resource level, the resource instance should be able to predict the next tasks (future state) based on the knowledge (partial or complete) related to the final objective.

This process should be applied to a single resource and/or to a network of resources. From possible-worlds knowledge and learning capacities, the system should be able to predict the impact of resource on the system state i.e. system time-response to requests, bandwidth bottlenecks, tasks, etc. Constructive or destructive interferences have to be assessed in the same phase. [Steinberg, 2001] stated about resources management: it is a hierarchical and recursive procedure, which objective is the evaluation of both feasibility (response-time and resource cost) and benefice (projected gain improvement). From cost functions, optimal paths (possible COAs), within space and time dimensions, could be generated (synchronously or asynchronously) for resources management. To limit the associated processing, hybrid management plans (partially static i.e. uncontrolled by the system source manager and partially dynamic) could be generated.

4.2 *Learning*

Learning is often the determining capability that sets the border between intelligent and non-intelligent systems. From learning, system components/agents performance could be weighed, optimizing performance for the next uses of the system. Simulated annealing, neural-networks, Bayesian networks and genetic algorithms, are learning technique instances. For example, [Pigeon *et al.*, 2001b] proposed a genetic algorithm approach for multi-agent architectures characterized by topology variations (components are not constant over the encountered cases) and a limited number of experimentations (number of used cases which do not tend toward infinity). This process is based on the evaluation of a fitness function from the final states/decisions. Then, a learning component could be used to optimize inference networks. For this achievement, the refinement would be performed to the models that connect the “object space”, “observation space”, “feature space” and “decision space” (figure 1).

As stated in the previous section, the main mathematical approaches of fusion assume exhaustiveness and certainty. In order to reach these conditions, within the application context, the learning component could be used to weigh, for example, probabilistic distributions, belief mass functions, fuzzy membership functions, etc. It could then propose a solution to minimize the incoherence related to the Open-World assumption. It can also lead to pattern discoveries in order to refine models generalization.

5. **Conclusion**

This paper proposed a process for military information system design. This approach is based on a merge between the existing fusion frameworks and also on the author's experience in data fusion. Specifically, the design is based on system objectives and related accuracies requirements, constrained by a determined sequence of events, in this case detect, identify, track and estimate of the future state (DITE). Hence, a five-dimension structure is proposed for data modeling and management: space (x,y,z), time (t) and possible worlds (w). On this foundation, data exploitation and resource management are performed with regard to network inference, data perfection conditions and general data fusion approaches. Learning process enhanced the system by an intelligent component performing optimization.

As stated in the introduction, military information system design is a challenge that would confer or withhold information superiority, which could represent military superiority especially in complex warfare such as urban operations or counterterrorism. Hence, the refinement of the design process as proposed in this paper should be considered as a priority that could be decisive for near-future engagements.

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